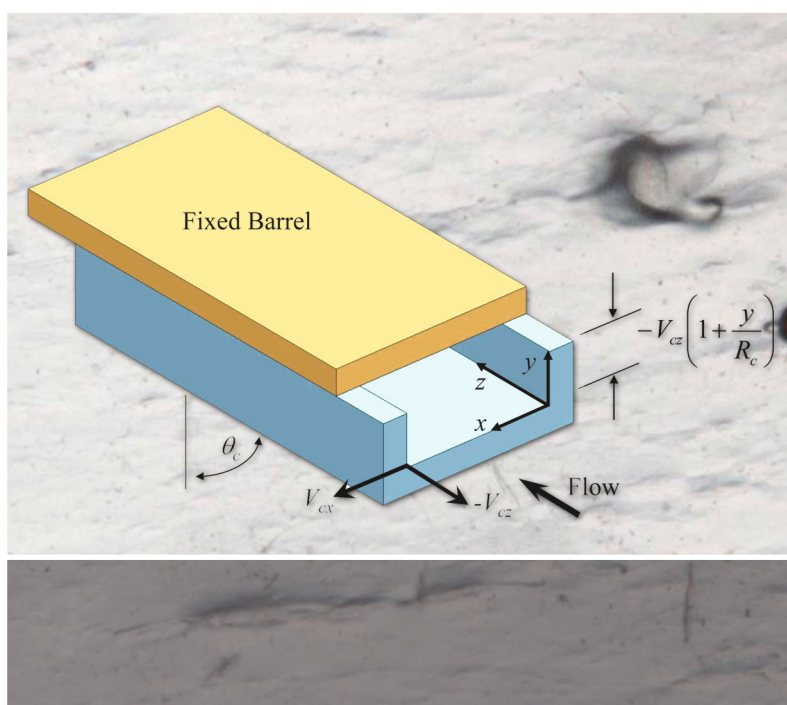Gregory A. Campbell
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# Analyzing and Troubleshooting Single-Screw Extruders



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# Preface

Classically, all prior extrusion books are based on barrel rotation physics. Literature developed over the past 15 years has led to this first book to be published based on the actual physics of the process–screw rotation physics. After the theories and the math models are developed in the first nine chapters, the models are then used to solve actual commercial problems in the remainder of the book. Realistic case studies are unique in that they describe the problem as viewed by the plant engineers and provide the actual dimensions of the screws. Knowledge is developed using a series of hypotheses that are developed and then tested, which allows a series of technical solutions. Several actual solutions are proposed with the final results that solve the problem then clearly presented. Overall, there is not a book on the market with this level of detail and disclosure. New knowledge in this book will be highly useful for production engineers, technical service engineers working with customers, consultants specializing in troubleshooting and process design, and process researchers and designers that are responsible for processes that run at maximum rates and maximum profitability.

Debugging and troubleshooting single-screw extruders is an important skill set for plant engineers since all machines will eventually have a deterioration in their performance or a catastrophic failure. Original design performance must be restored as quickly as possible to mitigate production losses. With troubleshooting knowledge and a fundamental understanding of the process, the performance of the extruder can be restored in a relatively short time, minimizing the economic loss to the plant. Common root causes and their detection are provided. Hypothesis testing is outlined in Chapter 10 and is used throughout the troubleshooting chapters to identify the root causes. Elimination of the root cause is provided by offering the equipment owner several technical solutions, allowing the owner to choose the level of risk associated with the process modification. Mechanical failures are also common with single-screw extruders, and the common problems are identified. Illustrations are provided with the problems along with many numerical simulations of the case studies. Collectively, these instruct the reader on how to determine and solve many common extrusion problems. About 100 case studies and defects are identified in the book with acceptable technical solutions. Lastly, we

hope that this book provides the information and technology that is required for the understanding, operation, and troubleshooting of single-screw extruders.

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# Acknowledgements

My interest in fundamental polymer research began in 1964 when I began my graduate career. My research efforts were strongly influenced by my mentor Professor Edward G. Bobalek, one of finest gentleman and innovative research minds I have ever met. My research philosophy was strongly influenced by many encounters with Ed before and after I defended my dissertation. One particularly important encounter occurred when I was lamenting that my dissertation research did not appear to be a really important breakthrough. He took a long draw on his ever present pipe and said "Greg, that is why we call it research and not search." From that time on I have always looked at my efforts as learning from the previous researchers that have laid the technical foundation in the area that is now being addressed. My role is thus to continue to build on that foundation when looking for a solution to the research challenge that I am currently addressing.

After leaving the University of Maine, I worked with wonderful groups of exceptional researchers at General Motors research, Mobil Chemical research, and Clarkson University. Many of these individuals spent their valuable time to help me hone my research skills. Probably the most influential individual was Dr. William Meluch; a true genius that I had the pleasure of working with for 13 years. Another good friend that had a major influence on my manner of approaching engineering research was Professor Art Fricke whom I collaborated with at the University of Maine and the University of Florida. My colleague Dr. Don Rassmussen at Clarkson University provided important guidance in all things thermodynamic.

My extrusion experience started when I directed process research at Mobil Chemical Research in the early 1980s. We developed and analyzed data on a 24 to 1 single-screw extruder with 12 infrared probes and 12 pressure probes using high-speed data acquisition. I then changed career paths and accepted a position at Clarkson University teaching chemical engineering while developing the Clarkson Polymer Processing Laboratory. The new concepts developed in this book were first recognized by Dr. Paul Sweeney when he was a graduate student in about 1988. I have to admit that it took considerable effort on Paul's part to convince me to even address these new concepts. Once we became convinced that it was important to complete the solution of the single-screw extruder analysis and bring the solution

# Contents

# 1 Single-Screw Extrusion: Introduction and Troubleshooting

This book was written to provide the extrusion process engineer with a resource for assessing and fixing process problems associated with the use of single-screw extruders. The authors have drawn on their complementary backgrounds; both have worked with industrial extruder design, analysis, and fundamental research in the mechanism, operation, and troubleshooting of the single-screw extrusion process. The use of single-screw extruders in production processes has progressed significantly over the past several decades. As a result, the number of single-screw extruders in use has increased dramatically as has the diameter and length of the machine, especially for melt-fed extruders used in large resin production plants. In addition, resin manufacturers have developed many new resins for final products such as extruded sheet, film, pipe, fibers, coatings, and profiles. The extruder is still the process unit of choice for producing pellets in the production of polymer materials. Two types of extruders are generally used in polymer production: single-screw extruders and twin-screw extruders. The material in this book will be confined to the analysis and troubleshooting of single-screw extruders. The rapid expansion of this part of the polymer industry has been accompanied by the need for many new extrusion engineers. Many of these engineers have not had formal training in the analysis of the extruder and screw design nor have they had extensive education in polymer materials, which would help in troubleshooting problems on production equipment.

All single-screw extruders have several common characteristics, as shown in Figs. 1.1 and 1.2. The main sections of the extruder include the barrel, a screw that fits inside the barrel, a motor-drive system for rotating the screw, and a control system for the barrel heaters and motor speed. Many innovations on the construction of these components have been developed by machine suppliers over the years. A hopper is attached to the barrel at the entrance end of the screw and the resin is either gravity-fed (flood-fed) into the feed section of the screw or metered (starve-fed) through the hopper to the screw flights. The resin can be in either a solid particle form or molten. If the resin feedstock is in the solid form, typically pellets (or powders), the extruder screw must first convey the pellets away from the feed opening, melt the resin, and then pump and pressurize it for a down-

stream process operation. This type of machine is referred to as a plasticating single-screw extruder. The barrel is usually heated with a minimum of three temperature zones. These different temperature zones are consistent with the three utilitarian functions of the screw: solids conveying, melting, and pumping or metering of the polymer.



**Figure 1.1**  Photograph of a highly instrumented 63.5 mm diameter extruder built by American Kuhne
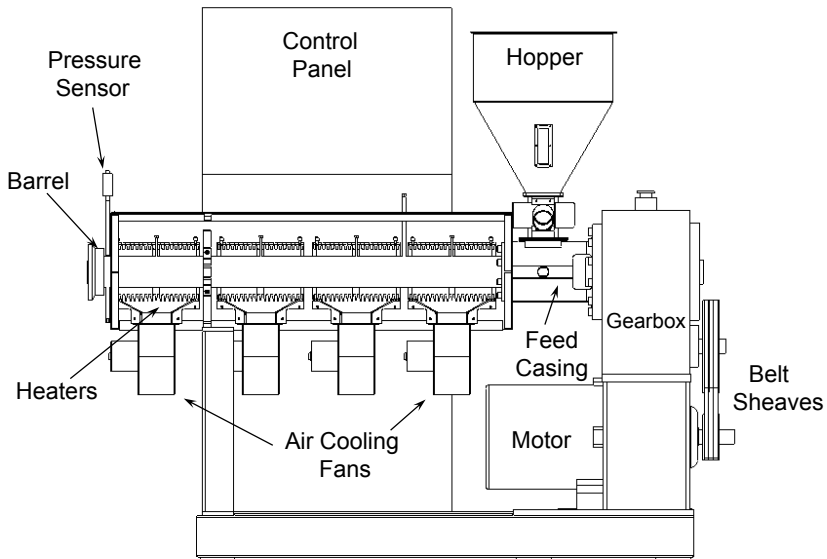


**Figure 1.2**  Schematic of a typical plasticating single-screw extruder. The extruder is equipped with four barrel heating and cooling zones and a combination belt sheave gearbox speed reduction drivetrain (courtesy of William Kramer of American Kuhne)

The single-screw plasticating process starts with the mixing of the feedstock materials. Typically, several different feedstocks are added to the hopper, such as fresh resin pellets, recycle material, additives, and a color concentrate. The recycle material typically comes from the grinding of edge trim, web material from thermoforming processes, or off-specification film and sheet. Often these components need to be dried and blended prior to adding them to the hopper. Next, the feedstock flows via gravity from the hopper through the feed throat of the feed casing and into the solids-conveying section of the screw. Typically this feed casing is cooled using water. The feed section of the screw is typically designed with a constant depth and is about 4 to 8 barrel diameters in axial length. Directly after the solids-conveying section is a section where the channel depth tapers to a shallow depth-metering section. The tapered-depth section is commonly referred to as the transition or melting section. In general, the metering section is also a constant depth, but many variations exist where the channels oscillate in depth. The metering section pumps and pressurizes the material for the downstream unit operations, including static mixers, screen filtering devices, gear pumps, secondary extruders, and dies. The total length of the extruder screw and barrel is typically measured in barrel diameters or as a length-to-diameter (L/D) ratio. Section lengths are often specified in barrel diameters or simply diameters.

The plasticator on an injection-molding machine is a specialized plasticating single-screw extruder. The plasticator has two main differences: there is a nonreturn valve on the tip of the screw, and the screw retracts as molten material accumulates between the nonreturn valve and the end of the barrel. Pressure is maintained on the accumulated material by a constant force applied to the shank of the screw via the drive system. This force is typically measured as a pressure applied to the shank and is referred to as the "back pressure." During the injection step of the process, the screw is forced forward, the nonreturn valve closes, and the material is injected into the mold. Additional information on the injection-molding process can be obtained elsewhere [1].

## ■ 1.1 Organization of this Book

This book has been organized so that the information is helpful in troubleshooting extruders and extrusion processes, and it is presented in a manner that is of maximum utility to extrusion engineers. Appendices have been provided that present the theoretical analysis and assumptions in developing the design equations used throughout this text. In order to assess extruder production problems, it is necessary to understand the nature of the polymer that is being extruded, the design of the extruder and screw, and the interaction of these as the extruder

is being operated. Numerous case studies are presented that demonstrate these interactions.

Knowledge of the geometry and mathematical description of a screw is required to understand the analysis of the functional sections of the screw and the troubleshooting of case studies. In Chapter 1 the geometry and mathematical descriptions are presented. Also in this chapter, the calculation of the rotational flow (also known as drag flow) and pressure flow rates for a metering channel is introduced. Simple calculation problems are presented and solved so that the reader can understand the value of the calculations.

Resin manufacturers go to extreme measures to produce a reproducible, high-quality, and useful polymer that is ready for final conversion to a product. Every time these polymers are passed through an extruder, however, the polymer has the potential to degrade, changing the chemical and physical properties of the resin. Degradation processes can often be the cause of extrusion problems. Chapter 2 begins with an introduction to how polymers are produced from the perspective of the type of chemical bonds that are important in different polymer families. It is beyond the scope of this book to discuss polymer production processes in detail. The discussion of polymerization is intended to aid the reader with a basic understanding on how the polymer is formed from its monomer. Knowing how the polymer was produced from its monomers will provide the engineer with the knowledge of how the extrusion process interacts with the polymer. This basic understanding will help in troubleshooting situations where the problem is the effect of the extrusion process on the stability of the polymer being extruded.

The physical properties that are important to polymer processing are presented in Chapters 3 and 4. Chapter 3 provides a basic understanding of the viscoelastic characteristics of polymers. In this chapter the fundamental concepts of polymer rheology are developed, and then there is a discussion of Newtonian and Power Law rheological responses of polymeric fluids, followed by a short introduction to the elastic nature of polymer melts. Chapter 4 presents the remaining physical properties, including friction coefficients (or stress at an interface), densities, melting fluxes, and thermal properties. These properties impact the performance of a resin during the extrusion process.

The fundamental processes and mechanisms that control single-screw extrusion are presented in Chapters 5 through 8. These processes include solids conveying, melting, polymer fluid flow, and mixing. The analyses presented in these chapters focus on easily utilized functions needed to assess the operation of the single-screw extruder. The derivation of these relationships will be presented in detail in the appendices for those who desire to explore the theory of extrusion in more detail.

The remaining Chapters 9 through 15 are devoted to different types of extrusion troubleshooting analyses. These chapters include presentations on scale-up tech-

niques, general troubleshooting, screw fabrication, contamination in finished products, flow surging, and rate limitations. The chapters are presented with actual case studies of extrusion troubleshooting problems with the detailed analytical approach that was used to address these problems. As part of this troubleshooting presentation, high-performance screws and their benefits are presented. Lastly, melt-fed extruders will be discussed. Melt-fed extruders are a special class of machines that are rarely discussed in the open literature.

Appendix A1 has a listing of the polymer abbreviations used in this book.

## ■ 1.2  Troubleshooting Extrusion Processes

All extrusion and injection-molding plastication processes will eventually operate at a performance level less than the designed level. This reduction in performance can be caused by many factors, including but not limited to control failures, a worn screw or barrel, or a process change such as processing a different resin. Moreover, an improper screw design or process operation can limit the performance of the machine and reduce the profitability of the plant. Other processes may be operating properly at the designed rate, but a higher rate may be required to meet market demands. In this case, the rate-limiting step of the process needs to be identified and a strategy developed to remove the limitation.

Troubleshooting is a process for systematically and quickly determining the root cause of the process defect. The troubleshooting process is built on a series of hypotheses, and then experiments are developed to prove or disprove a hypothesis. The ability to build a series of plausible hypotheses is directly related to the knowledge of the engineer troubleshooting the process. Our focus is on providing the knowledge for the proper operation of an extrusion process, helping determine typical root causes that decrease the performance of the machine, and offering methods of removing the root cause defect from the process.

The economic impact of a properly designed troubleshooting process can be significant, especially if the defect is causing very high scrap rates or production requirements are not being met. Returning the process to full production in a timely manner will often require subject matter experts from several disciplines or companies. An excellent example of a troubleshooting process is described next for a processing problem at the Saturn Corporation.

### 1.2.1 The Injection Molding Problem at Saturn

During the startup of Saturn Corporation's Spring Hill, Tennessee, plant in September of 1990, a serious splay problem was encountered for the injection molding of door panels from a PC/ABS resin [2]. Splay is a common term used to describe surface defects on injection-molded parts. The splay on the surface of the door panels created parts with unacceptable appearances after the painting process. The part rejection rate was higher than 25 %, high enough to nearly shut down the entire plant. Teams were formed from the companies involved to determine quickly the root cause for the splay. After a detailed analysis was performed, it was determined that the plasticating screw in the injection molder was not operating properly, causing some of the resin to degrade in the channels of the screw. The splay was created by the volatile components from the degradation of the resin. A high-performance Energy Transfer (ET) screw [3] was designed and built, eliminating the splay. A detailed discussion of the troubleshooting process at Saturn is presented in Section 11.12.5.

The troubleshooting project at Saturn is an excellent example of combining strengths from different companies to diagnose and eliminate a costly defect from a process.

## ■ 1.3 Introduction to Screw Geometry

In order to simulate an extrusion process or design a screw, the mathematical description of the screw geometry must be understood. This section provides the basic details that describe a screw and the complex mathematics that describe the channels.

The single-screw extruder screw can be single flighted or multiple flighted. A conventional single-flighted screw is shown in Fig. 1.3. This screw has a single helix wound around the screw root or core. Multiple-flighted screws with two or more helixes started on the core are very common on high-performance screws and on large-diameter melt-fed machines. For example, barrier melting sections have a secondary barrier flight that is located a fraction of a turn downstream from the primary flight, creating two flow channels: a solids melting channel and a melt-conveying channel. Moreover, many high-performance screws have two or more flights in the metering section of the screw. Barrier screws and other high-performance screws will be presented in Chapter 14. Multiple flights are very common on larger-diameter extruder screws, because this creates a narrower channel for the polymer melt to flow through, leading to less pressure variation due to the rotation of the screw. In addition, the multiple flights spread the bearing forces between

the flight tip and the barrel wall. Melt-fed extrusion processes will be discussed in detail in Chapter 15. The screw is rotated by the shank using either specially designed splines or by keys with rectangular cross sections. The mathematical zero position of the screw is set at the pocket where the screw helix starts. Most extruder manufacturers rotate the screw in a counterclockwise direction for viewers positioned on the shank and looking towards the tip. This rotation convention, however, is not standard.
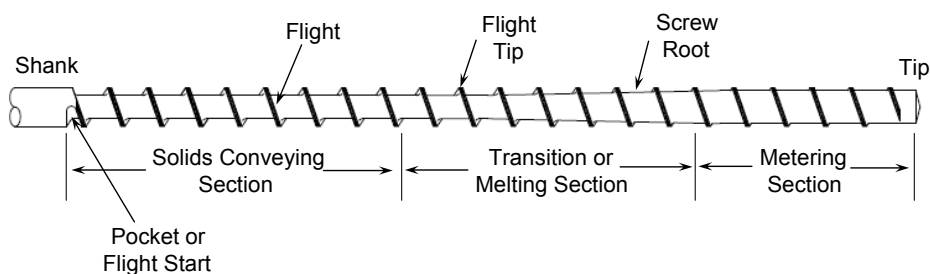


**Figure 1.3**  Schematic of a typical single-flighted screw
(courtesy of Jeff A. Myers of Robert Barr, Inc.)

The flight is a helical structure that is machined into the screw and extends from the flight tip to the screw core or root. The flight has a width at the flight tip called the flight land. The small clearance between the flight land and the barrel wall minimizes the flow of polymer back toward the feed section. The polymer that does flow between the clearances supports the screw and centers it in the barrel. The radial distance between the flight tip and the screw root is referred to as the local flight height or channel depth. The feed section usually has a constant-diameter core that has the smallest diameter, the largest channel depth, and the largest cross-sectional volume in the screw. The deep channel conveys the relatively low bulk density feedstock pellets into the machine. The feedstock is conveyed forward into the transition section or melting section of the screw. The transition section increases in root diameter in the downstream direction, and thus the channel depth decreases. Here, the feedstock is subjected to higher pressures and temperatures, causing the feedstock to compact and melt. As the material compacts, its bulk density can increase by a factor of nearly two or more. As the feedstock compacts, the entrained air between the pellets is forced back and out through the hopper. For example, a pellet feedstock such as ABS resin can have a bulk density at ambient conditions of 0.65 g/cm$^3$ while the melt density at 250 °C is 0.93 g/cm$^3$. Thus for every unit volume of resin that enters the extruder, about 0.3 unit volumes of air must be expelled out through the voids in the solid bed and then out through the hopper. The transition section is where most of the polymer is converted from a solid to a fluid. The fluid is then conveyed to the metering section where the resin is pumped to the discharge opening of the extruder. In general, the metering section of a conventional screw has a constant root diameter, and it has a

much smaller channel depth than the feed section. The ratio of the channel depth in the feed section to the channel depth in the metering section is often referred to as the compression ratio of the screw.

### 1.3.1 Screw Geometric Quantitative Characteristics

The book *Engineering Principles of Plasticating Extrusion* by Tadmor and Klein [4] has been used extensively in gaining an understanding of the fundamentals of extrusion processes. The following section endeavors to maintain the quality of the development of the screw geometry section of this classic text. Understanding the relationships between the screw geometry and the symbolic and mathematical representation of a screw is a critical beginning for understanding the rate, pressure, and temperature calculations. These functions related to the performance of single-screw extruders are developed later in this book and require an understanding of the screw geometry.

The geometry of a double-flighted screw and its nomenclature are presented in Fig. 1.4 using the classical description from Tadmor and Klein [4]. The nomenclature has been maintained to provide consistency with the classical literature and to provide some generality in the development of the symbols and equations that are used in extruder analysis.

Several of the screw geometric parameters are easily obtained by observation and measurement, including the number of flight starts, inside barrel diameter, channel depth, lead length, flight width, and flight clearance. The number of flight starts, $p$, for the geometry in Fig. 1.4 is two. The inner diameter of the barrel is represented by $D_b$, and the local distance from the screw root to the barrel
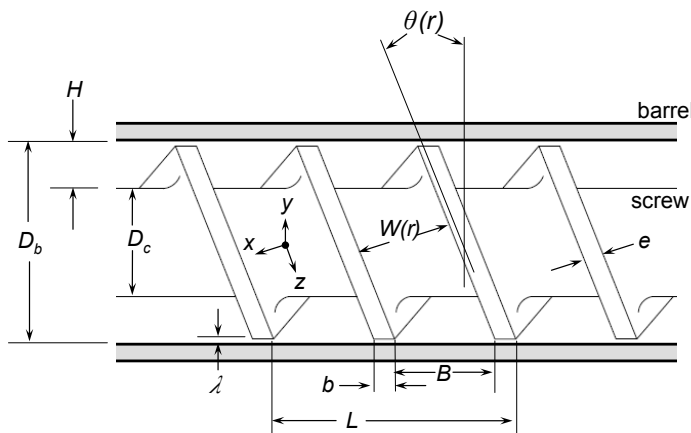


**Figure 1.4** A schematic of a double-flighted screw geometry

is $H$. The diameter of the screw core is represented by $D_c$. The mechanical clearance between the land of the screw flight and the barrel is $\lambda$. The mechanical clearance is typically very small compared to depth of the channel. The lead length, $L$, is the axial distance of one full turn of one of the screw flight starts. This is often constant in each section of the screw, but in some screws, such as rubber screws, it often continuously decreases along the length of the screw. A screw that has a lead length that is equal to the barrel diameter is referred to as square pitched. The flight width at the tip of the screw and perpendicular to the flight edge is $e$.

The remaining geometrical parameters are easily derived from the measured parameters presented above. Several of the screw parameters are functions of the screw radius. They include the perpendicular distance from flight to flight, $W(r)$; the width of the flights in the axial direction, $b(r)$; and the helix angle, $\theta(r)$, the angle produced by the flight and a plane normal to the screw axis. These parameters will be discussed later. At the barrel wall these parameters are subscripted with a $b$. The helix angle at the barrel wall is $\theta_b$ and is calculated using Eq. 1.1. The helix angle at the barrel wall for a square-pitched screw is 17.7°.

$$\tan\theta_b = \frac{L}{\pi D_b} \quad \text{thus} \quad \theta_b = \arctan\frac{L}{\pi D_b} \tag{1.1}$$

The relationship between the width of the channel perpendicular to the flight at the barrel interface, $W_b$, and the axial distance between the flight edges at the barrel interface, $B_b$, is as follows:

$$W_b = B_b\cos\theta_b = \left(\frac{L}{p} - b_b\right)\cos\theta_b = \frac{L}{p}\cos\theta_b - e \tag{1.2}$$

$$e = b_b\cos\theta_b \tag{1.3}$$

As mentioned earlier, several of the geometric parameters are a function of the radial position ($r$) of the screw. These parameters include the helix angle and the channel widths. The length of an arc for one full turn at the barrel surface is $\pi D_b$. At the screw surface the length of the arc for one turn is $\pi(D_b - 2H)$; the lead length, however, remains the same. This leads to a larger helix angle at the screw root than at the barrel surface. This analysis is for a flight width that does not change with the depth of channel. As discussed in Chapter 10, for a properly designed screw, the flight width will increase as the root of the screw is approached due to the flight radii.